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Rheological studies of polycaprolactone in supercritical CO₂

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Abstract

A high pressure parallel plate rheometer is utilised to probe the rheological properties of polycaprolactone (PCL) over a range of temperatures (80 to 120 °C) and CO₂ pressures (atmospheric to 100 bar). Interpretation of storage/loss modulus against angular frequency plots show that the reptation time of PCL can be significantly reduced by the addition of 60 bar CO₂. This reduction is equivalent to heating the polymer by 20 °C. Application of a time/temperature superposition, coupled with the Arrhenius equation, shows that the addition of CO₂ also lowers the activation energy to flow from 31.3 to approximately 21 kJ mol⁻¹.

Keywords: reptation; rheology; supercritical CO₂; polycaprolactone

1. Introduction

Polycaprolactone (PCL) is a semi-crystalline polymer possessing glass transition and melting temperatures of -60 and 60 °C, respectively. It is commonly used in a wide range of medical applications, for example tissue engineering [1-2] and drug delivery [3], as a result of its biocompatible and biodegradable nature coupled with a high compressive strength. In the melt phase, PCL displays a high viscosity, which results in elevated temperatures (above 140 °C) being required to process it [4]. This is a major problem when trying to incorporate thermally sensitive drugs or cells for biomedical applications; often causing them to denature or degrade [5].

Supercritical CO₂ (scCO₂) is becoming increasingly used to facilitate the processing of high viscosity polymers [6-7]. We have previously highlighted the ability of high pressure and supercritical CO₂ to absorb into PCL [8] and the depression of the melting point that occurs as a result [9]. The gas-like viscosity of scCO₂ enables it to diffuse into the free volume within amorphous regions of polymers. Once inside, it takes part in Lewis acid/base interactions with the carbonyl groups of PCL, weakening the intermolecular interactions between the individual polymer chains and increasing the free volume [10]. As a result, the chains experience greater mobility thereby reducing the viscosity of the polymer matrix [11-12]. This phenomenon is analogous to heating the polymer and therefore enables processing to occur at lower temperatures.

There are numerous publications on the thermal and physical effects experienced by polymers, and in particular PCL, on the addition of scCO₂ [9, 13-16]. However, there has been little research into what occurs at a molecular level. The reptation model, formulated by de Gennes [17] and developed further by Doi and Edwards [18], enables the chain dynamics of highly entangled polymers to be probed thereby providing an insight into its viscous flow and dynamic properties. This model focuses on the topological constraints on individual polymer chains, bestowed by the surrounding bulk polymer, which effectively constricts the chain to an imaginary tube. As a result, movements can only occur laterally with a “snake-like” motion. The reptation time is given by the time it takes for the polymer chain to diffuse through one length of the imaginary tube. Development of this theory enables the reptation time to be determined as the reciprocal angular frequency at the point where the storage and loss moduli intersect during oscillation experiments [18-22]. In addition, repetition of these studies at various temperatures or stresses leads to calculation of the respective shift factors, allowing predictions to be made at further time decades [23]-[24].

To the authors knowledge no reptation studies have been conducted on polymers in the presence of scCO₂. Therefore, the aim of the current study is to understand the effect of high pressure and supercritical CO₂ on the reptation time of a PCL grade with a molecular weight above the critical entanglement molecular weight. Rheological experiments are performed over a range of temperatures (80 to 120 °C) and CO₂ pressures (atmospheric to 100 bar), below the CO₂ saturation limit within PCL [8], using a high pressure parallel plate rheometer. From these results the reptation times at each condition are analysed and compared. In addition a time-temperature superposition is applied to the rheological data at each pressure enabling the activation energy to flow to be calculated using the Arrhenius equation and the effects of pressure to be further probed.

1.1 Materials

Polycaprolactone (CAPA 6800) (M_w 120 kDa; PDI 1.74 as specified by the manufacturer) was supplied in pellet form by Perstorp UK Ltd. (Warrington, UK). CO₂ (purity 99.9 %v/v) was obtained from BOC (Manchester, UK) and used as received.

1.2 Production of PCL plaques

Plaques (150 x 150 x 1 mm) of PCL were produced by compression moulding using a Moore E1127 hydraulic hot press (George E. Moore & Sons Ltd, Birmingham, UK) which was preheated to 200 °C. Briefly, the polymer pellets (30 g) were placed into a mould (150 x 150 x 1 mm) which was then inserted into the press. The mould was allowed to warm for 5 minutes before applying a load of 10 kN for a further 5 minutes. The plaques were removed from the press and allowed to cool to room temperature. During cooling recrystallisation occurred, restoring the original crystallinity of the pellets (~60 %). Discs, with a radius of 10 mm, were then cut from the plaques for use in the rheometer.

1.3 Reptation analysis

Rheological analyses were performed using a Physica MCR301 rheometer (Anton Paar, Hertford, UK) with a high pressure parallel plate geometry of 20 mm in diameter and with a 1 mm gap (PP20/pr). In a typical experiment, a polymer disc was added to the lower plate of the preheated rheometer, to fill the 1 mm gap between the plates. The rheometer was then sealed and CO₂ charged into the vessel, using an ISCO high pressure syringe pump Model 2400 (Teledyne ISCO, Lincoln, NE, USA) to generate the desired pressure. The disc was allowed to soak for 5 minutes, prior to analysis, to allow the CO₂ to diffuse into the polymer. Oscillation tests were performed in which the angular frequency was varied on a log scale over 14 data points from 0.2 to 100 rad.s⁻¹. At each angular frequency the torque was allowed to stabilise, without any time constraints, prior to recording any data. Typically, each analysis took 14 minutes.

Initial viscosity analyses showed that the Newtonian region of PCL occurred between a shear rate of 0.02 and 0.32 s⁻¹ (data not shown). A series of strain sweeps were therefore performed over a range of angular frequencies to determine the strain required to obtain a shear rate within the Newtonian region. In light of this analysis, the strain was also adjusted from 100 to 0.2 % throughout the experiment to maintain a shear rate within the viscoelastic region. The storage (G') and loss (G'') moduli were determined for a range of temperatures (80 to 120 °C) above the melting point of PCL and CO₂ pressures (atmospheric to 100 bar). Three analyses were performed for each condition to give data confidence and the average G' and G'' values were then plotted against angular frequency (ω). The error bars on the plots represent ± 1 standard deviation from the mean.

1.4 Statistical Analysis

Statistical analyses were performed on either the angular frequencies at the intersection of the storage and loss moduli or the calculated reptation times, using Microsoft Excel. Analyses were

calculated using ANOVA and the Least Significant Difference (LSD) at the 5 % confidence level. Any differences in the results were considered significant if the p-value was less than 0.05.

2. Results and Discussion

2.1 Effect of temperature on the atmospheric rheological properties of PCL

Frequency sweeps were performed on PCL at atmospheric pressure over a range of temperatures (80-120 °C) above the melting point (~60 °C). Oscillation analyses were repeated three times for each condition and the average storage (G') and loss (G'') moduli plotted against the angular frequency (ω) (Figure 1). The error bars in the figure are given by ± 1 standard deviation from the mean.

Each of the conditions analysed generated typical responses of linear polymers with narrow polydispersity indexes (PDI) as governed by the Maxwell model (Figure 1) [25]. This model gives rise to two equations for the storage and loss moduli:

$$G'(\omega) = (G_p \omega^2 \tau^2) / (1 + \omega^2 \tau^2) \quad (1)$$

$$G''(\omega) = (G_p \omega \tau) / (1 + \omega^2 \tau^2) \quad (2)$$

where G_p is the plateau modulus, ω is the angular frequency and τ is the reptation time of the polymer.

The Maxwell model states that at low angular frequencies G' is proportional to ω^2 and G'' is proportional to ω for linear polymers with low PDIs [26]. A plateau in G' is also observed at high frequencies as the material becomes inflexible and rigid under rapid motion.

The results of the frequency sweeps at a range of temperatures (Figure 1) clearly show a horizontal shift along the angular frequency axis as the temperature of the polymer is increased. This shift is created by a decrease in both G' and G'' at a given frequency for low angular

frequencies. As these values make up the real and imaginary parts of the dynamic shear modulus (G^*), respectively [27], this property needs to be evaluated in order to determine the cause of the horizontal shift. In an oscillation analysis a constant shear strain is applied to the polymer at a set angular frequency. The resultant shear stress required to produce this strain is then recorded and G^* is calculated as:

$$G^* = \text{Shear stress} / \text{shear strain} \quad (3)$$

Above the melting point of a crystalline polymer short range motions of the polymer segments occur rapidly however, long range translation motion is restricted by entanglements between neighbouring chains. On increasing the temperature of the polymer, thermal expansion occurs which increases the free volume of the polymer and as a result enables more translational movement [28]. In addition, more energy is supplied to the polymer chains, increasing their mobility. These two factors reduce the force and therefore stress required to shear the material and consequently the dynamic shear modulus is also reduced. This phenomena gives rise to the reduction in both the storage and loss moduli and therefore the apparent horizontal shift in the traces (Figure 1). Horizontal shifts observed on increasing the experimental temperature are well characterised and leads to calculation of the activation energy to flow via a time-temperature superposition as discussed later [29].

The Maxwell equations (Equations 1 and 2) can also be used to calculate the reptation time of a polymer. Equating these two equations at the point where the storage and loss moduli curves intersect leads to the following expression for the reptation time:

$$\tau = 1 / \omega_{(G'=G'')} \quad (4)$$

where τ is the reptation time of the polymer and $\omega_{(G'=G'')}$ is the angular frequency at the point where G' and G'' intersect.

Calculation of the reptation time at each of the conditions shows an almost 50 % reduction on heating from 80 to 100 °C and a 30 % reduction on heating the material by a further 20 °C. This reduction occurs for two reasons. At temperatures just above the melting point of the polymer, the individual chains remain tightly packed together restricting the tube diameter through which the polymer chain will reptate. In addition, the energy of the chain will be relatively low, slowing its movement. Due to the thermal expansion of materials, heating the polymer causes the free volume between the polymer chains to increase thereby expanding the tube diameter and facilitating reptation. In addition, the rise in temperature will supply the polymer chain with more energy, increasing its mobility. These two factors aid reptation and therefore the reptation time of the polymer is reduced on heating.

The temperature dependence on the rheological properties of polymers is often assessed using a time-temperature superposition in which each of the curves are shifted along the horizontal axis to a reference temperature [23]. In this case, a reference of 100 °C was chosen as this temperature is most commonly used by other researchers when performing rheological studies on PCL [30-31]. The shift factors required to transpose each curve were then calculated as the ratio between the two angular frequencies:

$$\text{Shift factor}(a_T) = \omega_{\text{Experimental}} / \omega_{\text{Reference}} \quad (5)$$

where: $\omega_{\text{Experimental}}$ is the angular frequency at the experimental temperature; and $\omega_{\text{Reference}}$ is the angular frequency at the reference temperature.

As the isotherms have identical shapes the time-temperature superposition was found to be successful with similar shift factors obtained for each of the viscoelastic properties. On plotting the temperature dependence of the shift factors, Arrhenius behaviour was observed for this data set (data not shown). Use of the Arrhenius equation (Equation 6) then enabled an

activation energy to flow of 31.3 kJ mol^{-1} to be obtained for PCL. This value is consistent with results published previously in which activation energies of between 32 and 41 kJ mol^{-1} were obtained, using the same method, for a range of different molecular weight PCL grades at atmospheric pressure [30-32].

$$\ln a_T = (E_a/R)[(1/T)-(1/T_0)] \quad (6)$$

where: E_A is the activation energy to flow; R is the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$); T_0 is the reference temperature (K); and T is the experimental temperature (K).

2.2 Effect of CO₂ pressure on the rheological properties of PCL

Similar frequency sweeps were performed at 80 , 100 and 120°C over a range of pressures in order to evaluate the effect of CO_2 pressure on the reptation time of PCL. Three analyses were again performed for each condition, to generate confidence in the data, and the average G' and G'' values are plotted against angular frequency (Figure 2). The error bars in the figure are given by ± 1 standard deviation from the mean.

Responses typical of linear polymers were again generated at each condition as was to be expected (Figure 2). Comparison of the curves generated at atmospheric pressure and in the presence of 60 bar CO_2 show a distinct shift towards higher angular frequencies on the addition of the CO_2 . This shift is similar to that seen on increasing the temperature (Figure 1) and indicates a decrease in the dynamic shear modulus of the polymer created by a reduction in the torque required to produce a given strain (Equation 2). It is well understood that raising the pressure imparted on a polymer increases the dynamic shear modulus as the free volume between the chains becomes compressed thereby restricting the movement of the polymer

chains [28]. However, in this situation, the opposite occurs showing it to be an effect of the CO₂ addition alone rather than a pressure effect.

The ability of CO₂ to diffuse into the amorphous regions of PCL, whereupon it undergoes Lewis acid/base interactions with the carbonyl groups in the polymer chain, is well characterised [8, 10]. This weakens the intermolecular interactions between the individual polymer chains, increasing the free volume of the polymer and also the mobility of the chains. As a result of these factors, less force is required to cause the polymer to flow and therefore the dynamic shear modulus is reduced, along with the storage and loss moduli, leading to the horizontal shift in the traces.

Although a horizontal shift in the traces is observed on the addition of 60 bar CO₂, there is little movement as the pressure is increased further. We have previously shown that as the CO₂ pressure is elevated the concentration dissolved within PCL also increases [8]. This excess should expand the free volume further leading to large reductions in the dynamic shear modulus, however this is not observed here. As mentioned above, the addition of pressure generated by non-soluble gases causes compression of the polymer matrix and therefore a reduction in the free volume, leading to increased shear moduli. As the CO₂ pressure is increased above 60 bar it is therefore likely that the two effects compete against each other with the CO₂ absorption mildly dominating, leading to only a subtle horizontal shift.

Calculation of the reptation time at each pressure (Table 2) shows a significant decrease upon the addition of CO₂. This reduction is analogous to heating the polymer from 80 to 100 °C (Table 1) and suggests that the addition of 60 bar CO₂ can reduce the processing temperature of PCL by 20 °C leading to a more economical process and reducing the likelihood of any bioactives degrading. As mentioned in the previous section, CO₂ is able to penetrate into the amorphous regions of polymers where it expands the free volume and increases the mobility of the polymer chains. Both of these processes contribute to the reduction in reptation time as enlarging the

free volume of the polymer reduces the tortuous nature of the reptation path, whilst enhancing the mobility of the chains, allowing their faster transient motion through the bulk polymer.

Despite the large reduction in the reptation time observed on the addition of CO₂, raising the pressure further had little effect (Table 2). As discussed above, previous CO₂ absorption experiments on PCL have shown that a greater concentration of CO₂ becomes dissolved in the polymer on raising the pressure [8]. This increase in CO₂ absorption will enhance the effects discussed, leading to a greater free volume and chain mobility and therefore a reduced reptation time. However, the increase will also raise the pressure surrounding the polymer, forcing the chains closer together again [33]. This hinders the expansion of the free volume, diminishing the effect of the absorbed CO₂ on the reptation time.

A large reduction in the reptation time on the addition of CO₂ coupled with a negligible effect as the pressure was increased further was also experienced at both 100 and 120 °C (Figure 3). It can be seen however, that the effect of the CO₂ addition diminishes as the experimental temperature is increased with only a 29 % reduction observed at 120 °C compared to a 49 % reduction at 80 °C. The results from the previous two sections have illustrated how both temperature and CO₂ pressure can enhance the free volume of the polymer, reducing the tortuous nature of the reptation pathway, whilst also increasing the mobility of the polymer chains. We have also discussed how both of these factors contribute to the observed reductions in the reptation times. It therefore follows that at high temperatures, as the polymer has already undergone thermal expansion and the chains possess a greater mobility, the effects generated by the addition of CO₂ become less dominant.

As the frequency sweeps were performed over a temperature range for each of the pressures a time-temperature superposition, to a reference temperature of 100 °C, was applied to the data sets. Each of the isotherms could be superimposed onto the reference trace and similar shift factors were obtained for each rheological parameter (Equation 4) (data not shown). The

temperature dependence of the shift factors displayed Arrhenius behaviour and therefore the activation energy to flow at each pressure could be calculated from the Arrhenius equation (Equation 5).

The activation energy to flow of PCL at atmospheric pressure was calculated previously as 31.3 kJ mol^{-1} , however, on the addition of 60 to 100 bar CO_2 , the energy required was considerably reduced to between 20.7 and 22.2 kJ mol^{-1} , respectively (Table 3). This reduction is created by the increased free volume and chain mobility afforded by the polymer on the absorption of CO_2 which reduces the energy required for the polymer chains to move and therefore the polymer to flow.

3. Conclusions

The rheological properties of PCL over a range of temperatures (80 to 120°C) and CO_2 pressures (atmospheric to 100 bar) have been evaluated. On increasing the temperature there is an obvious shift along the horizontal axis to higher angular frequencies leading to a significant reduction in the reptation time of PCL. The time-temperature superposition of these plots, in line with the Arrhenius equation, led to the calculation of an activation energy of flow of 31.3 kJ mol^{-1} , which is consistent with those values reported in the literature. Upon the addition of 60 to 100 bar CO_2 a reduction in the reptation time of PCL was again observed, however varying the pressure had little effect. The activation energy to flow also reduced by approximately 10 kJ mol^{-1} on the addition of CO_2 but again pressure displayed little effect.

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Figures

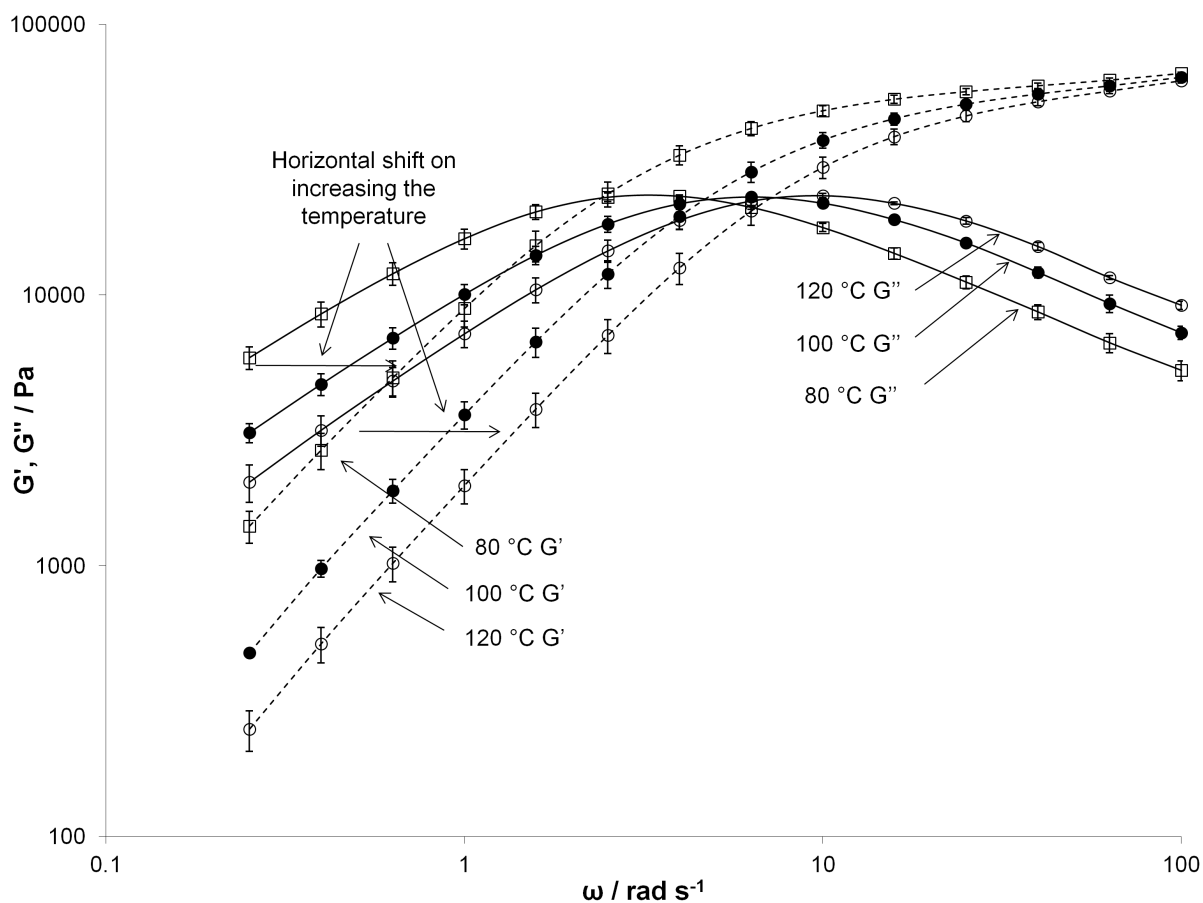


Figure 1: Plots of the storage modulus (G') and loss modulus (G'') against angular frequency for PCL at atmospheric pressure over a range of temperatures. The results show a clear horizontal shift to higher angular frequencies as the temperature is raised, indicating a reduction in the reptation time. $p < 0.0001$, 5 % LSD = 0.94 rad s^{-1} .

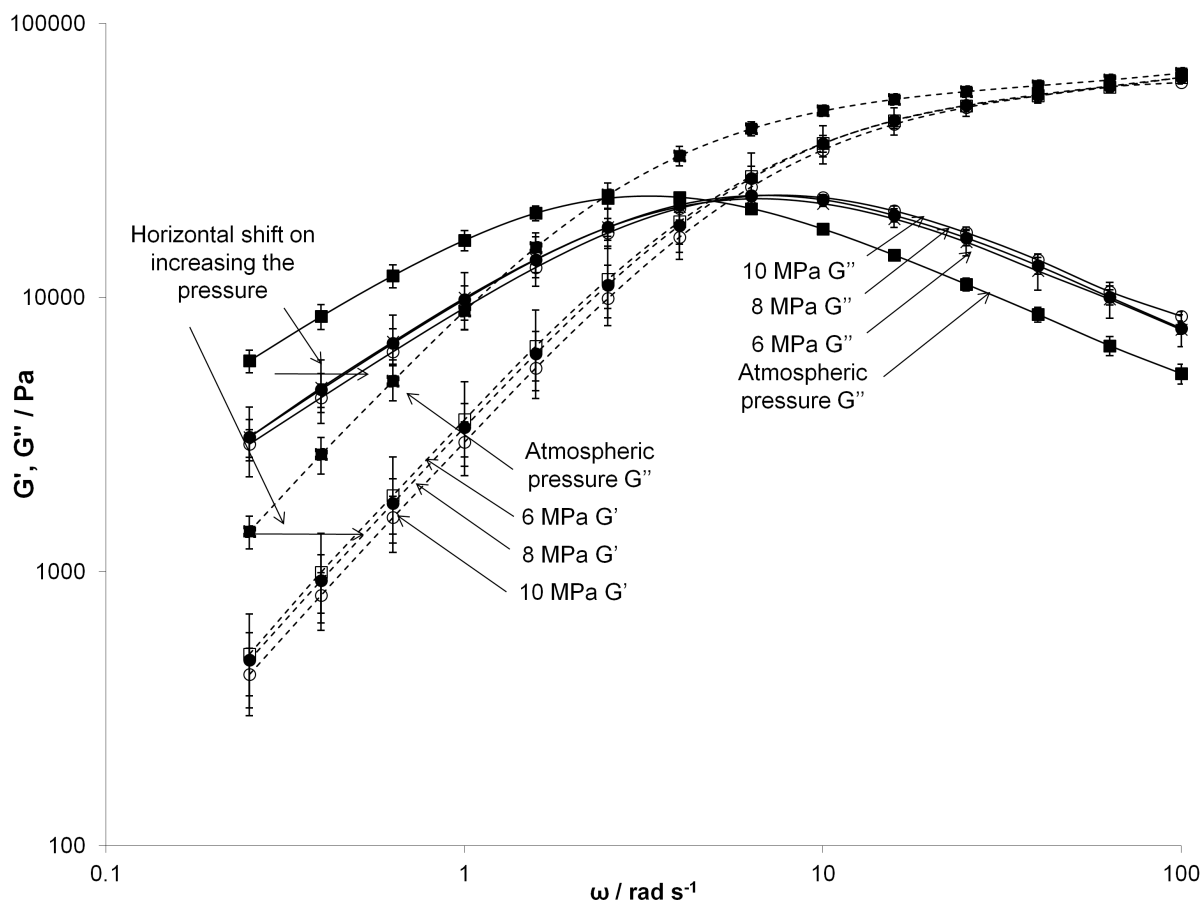


Figure 2: Plots of the storage modulus (G') and loss modulus (G'') against angular frequency for PCL at 80 °C over a range of CO₂ pressures. The results show a clear horizontal shift to higher angular frequencies on raising the pressure indicating a reduction in the reptation time. $p = 0.0044$, 5 % LSD = 1.50 rad s^{-1} .

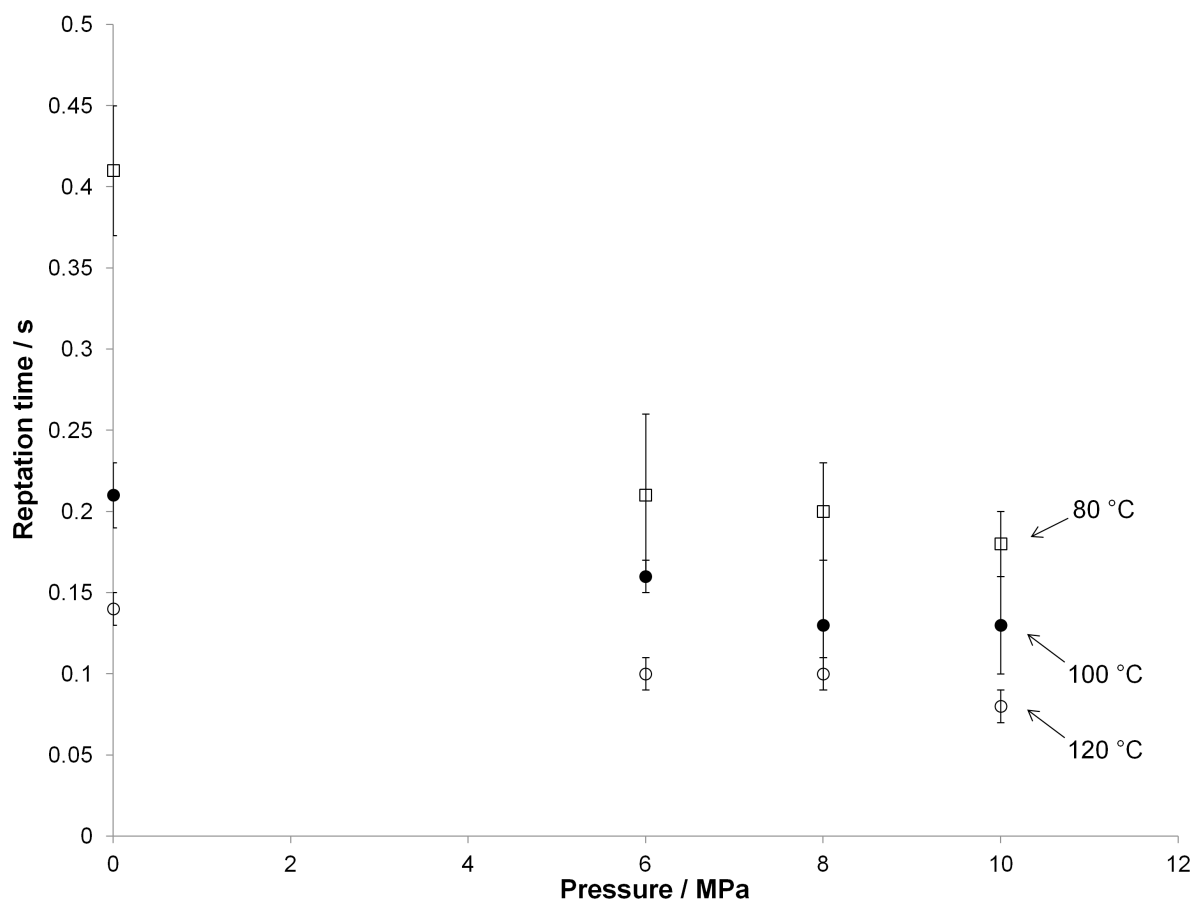


Figure 3: Change in reptation time on varying the pressure at a range of temperatures. As the experimental temperature is increased the effect of the addition of CO₂ becomes less significant. 80 °C $p < 0.0001$ 5 % LSD = 0.07 s; 100 °C $p = 0.0499$ 5 % LSD = 0.0499 s; and 120 °C $p = 0.001$ 5 % LSD = 0.0218 s.

Tables

Table 1: The reptation times of PCL over a range of temperatures. Raising the temperature of the polymer significantly reduces the reptation time.

Temperature (°C)	G' G'' crossover frequency (rad s ⁻¹)	Reptation time (s)
80	2.4	0.41 ± 0.05
100	4.6	0.21 ± 0.03
120	7.2	0.14 ± 0.01

Significant difference between conditions $p < 0.0001$, 5 % LSD = 0.94 rad s⁻¹

Table 2: Calculation of the reptation time of PCL at 80 °C over a range of pressures. The addition of scCO₂ significantly reduces the reptation time and a general trend of decreasing reptation time with increased pressure is observed.

Conditions		G' G'' crossover frequency (rad s ⁻¹)	Reptation time (s)
Temperature (°C)	Applied CO ₂ Pressure (bar)		
80	-	2.44	0.41 ± 0.05
80	60	5.03	0.21 ± 0.06
80	80	5.17	0.20 ± 0.03
80	100	5.95	0.18 ± 0.03

Significant difference between conditions $p = 0.0044$, 5 % LSD = 1.50 rad s⁻¹

Table 3: Activation energy to flow of PCL over a range of pressures. The addition of CO₂ reduces the activation energy to flow.

Applied CO ₂ Pressure (bar)	Activation energy to flow (kJ mol ⁻¹)	R ² value of Arrhenius plot
Atmospheric	31.3	0.9899
60	20.7	0.9587
80	20.7	0.9896
100	22.2	0.9692

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